Universal Experimental Measurement System
«Sun-Walker»

Master Thesis
Electrical Engineering
Reg No:
# Universal Experimental Measurement System «Sun-Walker»

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Master Thesis

Electrical Engineering

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**Title**

Universal Experimental Measurement System «Sun-Walker»

**Keywords**
To my wife Elmira
and my sons Lennar and Aydar.
Their courage and support helped me to win.
To entire my family.
Their love and hopes gave me strength
Acknowledgement

I would like to express my huge gratitude to my Teacher – Professor Bjorn Sohlberg. He gave me power to control systems.

I would like to thank all professors and staff-members of Electrical Engineering department and Dalarna University for the unique knowledge they have given to me and for the excellent conditions for study.

I would like also to extend my thanks to the great Swedish people for the hospitality and provided opportunity for training.
ABSTRACT

This Thesis project is a part of the research conducted in Solar industry.

ABSOLICON Solar Concentrator AB has invented and started production of the prospective solar concentrated system Absolicon X10. The aims of this Thesis project are designing, assembling, calibrating and putting in operation the automatic measurement system intended to evaluate distribution of density of solar radiation in the focal line of the concentrated parabolic reflectors and to measure radiation from the artificial source of light being a calibration-testing tool.

On the basis of the requirements of the company’s administration and needs of designing the concentrated reflectors the operation conditions for the Sun-Walker were formulated.

As the first step, the complex design of the whole system was made and division on the parts was specified. After the preliminary conducted simulation of the functions and operation conditions of the all parts were formulated.

As the next steps, the detailed design of all the parts was made. Most components were ordered from respective companies. Some of the mechanical components were made in the workshop of the company. All parts of the Sun-Walker were assembled and tested. The software part, which controls the Sun-Walker work and conducts measurements of solar irradiation, was created on the LabVIEW basis. To tune and test the software part, the special simulator was designed and assembled.

When all parts were assembled in the complete system, the Sun-Walker was tested, calibrated and tuned.
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1 INTRODUCTION

1.1 Preface

The second half of the XXth century is marked by birth and rapid expansion of the ecological movement in the world. Humanity has recognised vital importance of a significant decrease in the negative influence on the nature. The clear understanding that further pollution of the environment threatens health and the very existence of the Humanity has led to development of the national and international ecological legislation. Fast developing and improving the ecologically safe technologies have allowed decreasing pollution with solid and liquid wastes in relatively short time especially in developed countries. Moreover, reclamation of the wastes and replacement of the most hazardous materials in production became very profitable.

However, in the energy production area, the situation is not so optimistic. Up to now it has not been possible to find really new sources of energy. Great hopes, which were set on the nuclear and thermonuclear power, were not justified. Nuclear energy, which looked like a-pure energy at the stage of energy production, turned out to be a problem of the very dangerous and hazard wastes. Thermonuclear energy, which in the fifties seemed as an inexhaustible source of energy, has not started to work up to now. The research works have been conducting in this area that put off the possible start of thermonuclear energy exploitation to unpredictable time. The existing technologies do not allow maintaining the temperature of the plasma at 100 million degrees centigrade during the time, which will be enough to use it for producing energy. The modern/current idea to use Helium-3 from the Moon as a possible fuel for the future thermonuclear reactors and possible energetic panacea from the global energy-crisis looks much more fantastic if to take in account that in this case, it would be necessary to reach the plasma temperature up to one billion (!!!) degrees centigrade. The technologies that allow reaching and maintaining this temperature do not exist yet, and now nobody can shape them in at least general way.

Another problem is that existing energy production technologies have unacceptably low efficiency. If to take in account all energetic expenses and losses in the whole technological flow chart related with extraction, transportation, storage energy carrier and electrical energy generation, it becomes clear how wasteful the current production technologies are.

Unlike solid and liquid wastes, the processing of energy production wastes is very difficult. The existing technologies of energy production wastes utilization are premature and rather expensive.

The most energy sources in the world now are direct burning oil, gas and coal. As it was noticed above, this method shows extremely low efficiency where significant part of energy loses and heat goes to atmosphere. Also, energy generation using conventional fuels leads to pollution of the atmosphere by foul gases and solid particles, which maintain the Greenhouse effect and the ozone layer destruction.

Moreover, direct burning oil and gas is impermissible profusion because they are the valuable raw material for the chemical industry. As early as in the early 20th century, the famous chemistry scientist Mendeleyev said that to burn oil was the same as to burn banknotes.

Actually, Humanity has the biggest and almost eternal thermonuclear reactor – the Sun. All kinds of renewable energy on the Earth is solar energy in different forms. To elicit this energy from environment with the maximum efficiency is the main challenge for the Humanity.

Solar radiation allows getting thermal energy and electro-energy in any suitable place. Direct utilization of solar energy excludes mechanical parts (turbines and electromechanical generators) and necessity to transfer energy for long distance.
The solar systems, which would be able to produce thermal energy and electricity simultaneously, usually have less the specific price per kWh of the obtained energy owing to higher efficiency and possibility to use the common structure parts.

Hot water is produced at useful for application temperatures such as building heating and domestic hot water boilers, as well as many commercial and agricultural applications that require low-degree heat. The motivation for the development of the solar systems combination (PV/T – Photovoltaic/Thermal) is twofold: in the short term, to produce photovoltaic power and solar heating water at a cost which is competitive with other renewable energy technologies, and in the longer term, at a cost which is lower than it is possible with current technologies. To achieve this aim, the PV/T collectors must have an inherent advantage over other photovoltaic and thermal technologies.

Most photovoltaic and thermal collectors used for similar applications are flat plate collectors. The most prospective way to reach the competitive efficiency is applying the concentration for the PV/T solar receivers. This technology was named CPV/T – Concentrated Photovoltaic/Thermal. The primary advantage of the CPV/T system is that concentrated light allows significant reduction in the area of solar cell coverage, the main cost driver in a flat plate system.

Thermal energy generated could be considered as a byproduct due to the necessity to cool the cells, but in appropriate applications, the thermal energy is equally valuable. A secondary advantage of the CPV/T system is the efficient use of space inherent in combining electrical and thermal energy generation, which may be advantageous on rooftops or in other applications where space is limited. The challenge in the development of the CPV/T system is to design a robust collector with a clear pathway to more rapid cost reduction than the incumbent flat plate technology, and to optimize the performance within the cost constraints.
1.2 Background of the problem

The project oriented to create a combined concentrated solar collector was launched in 2002. The project involved around 10 other projects at, among others, the Universities in Borlange, Lund, and Uppsala, as well as the Royal Institute of Technology (KTH) in Stockholm.

Absolicon Solar Concentrator was established in 2007 and the first demonstration installations were built in Sweden and Germany.

Today Absolicon AB is starting the serial production of the most prospective Solar Concentrating System X10. The solar collector X10 produces both electricity and thermal heat in the same module, thanks to the Double Solar Technology™. [1]

The X10 is a solar collector that simultaneously generates the two forms of energy most used in the daily life: heat and electricity. This is possible as it combines a photovoltaic panel and a solar thermal collector in the same module.

It consists of a cylinder-parabolic reflector that concentrates the light of the sun ten times onto the receiver. It is equipped with the latest generation of photovoltaic technology and a solar tracking system. For the tracking, special electrical custom-designed high quality linear actuators are used. The objective is to automatically turn the X10 so that the sunlight always is focused onto the cells. The tracking system has a built-in program that automatically protects the photovoltaic cells from being overheated or from storms. If the temperature exceeds a certain value, the X10 automatically turns away the receiver from the sun.

The solar tracking system is controlled by a PLC control system, the heart of an X10 installation. Its main function is to ensure that the X10 follows the sun throughout all the day. It also includes an integrated web server that allows the remote control of X10 from any computer connected to the Internet.

The X10 can be installed on the ground as much as on a rooftop thanks to its robust construction. The construction is optimized for installations larger than 20m². The X10 is offered in four different lengths; 6, 10, 14 and 18 meters. These different lengths can be linked together in series for installations without any surface restrictions, i.e. everything between 20m² - 100 000 m² is possible to install with the X10.

The basic component of the concentrating system is 2 meters cylinder-parabolic reflector (CPR) (Fig. 1). The CPR consists of the frames, mirror, internal rails and glass cover. The mirror is the steel plate covered with a reflective film for the best reflection. The design of the frame and shape of the mirror were simulated using special software to reach the appropriate shape, which shall be able to provide the concentration of the solar radiation on the receiver.

Fig. 1 Cylinder-parabolic reflector
However, the final efficiency of the real systems depends on many factors, e.g. the ability of the production technologies to produce the reflectors of the defined shape, the shape and location of the receiver, its angle relatively the focal line. Also the concentrated solar technologies require the specific kind of solar cells because the partial shadowing on the solar cell, which are connected in series could lead to the extra electricity and thermal loads and respectively to the self-damaging of the shadowed cells. Usually installing the bypass diodes could solve this problem. From this point of view it is very important to know the irradiation situation on the end sides of the reflectors to design the respective electrical circuit of the diodes connection.

The existing experimental and theoretical data about the operation conditions of the combined receivers for the concentrated solar system are not sufficient for the proper design of the high-efficient solar concentrated collectors.

Figure 2 shows the possible improprieties in the design performance. In theory, the solar radiation has to be collected in narrow focal line exactly in the center of the solar cell on the receiver. However, we could note that the focal line of the mirror is located significantly above the center of the solar cells and the variation of the irradiation density distribution is observed along the receiver. So, significant discrepancy between the desirable and real result is the sequence of the insufficient knowledge about behavior of the components of the system and their combination and also about the influences of production technologies.

Also, it is very important to have valid information about the solar system state after the different kinds of tests. The proper knowledge about after-effects from of different influences helps to improve the system design and production technologies.

So, to solve the problems which were mentioned above it is critically important to have the universal measurement tool which would be able to conduct different tests in any point of the reflector's volume, to collect the data automatically and transfer them in the form convenient for the processing, storage and analysis. It has to be a reliable automotive measurement system from the mechanical, electrical and software components, which has to be able to put different (temperature and photo) sensors in desirable places in the reflector's volume. The System has to have enough flexibility to test the most important components of the real receivers.

The first destination of the future measurement system is collecting the experimental data about the existing solar collectors to improve their construction and to test the possible performance of the reflectors of the next generation, which is planned to design.
Also, the additional application for the future testing system would be calibration and periodical verification of the solar simulator, which is intended to test the receivers of the solar systems. As far as the receivers of concentrated solar system X10 work under the concentrated irradiation with power density up to 20 000W/m$^2$ the special simulator was ordered. The design of this simulator allows radiation on the surface with dimensions compatible with the receivers’ size. However, the superpower lamps, which can provide the necessarily radiation are liable to fast aging. To be sure in the testing results it is very important to conduct periodical verification of the solar simulator.
1.3 Project Task

The Project task is to design, develop, calibrate, and put into operation the measurement equipment intended to evaluate the location of the focal line and its light density distribution of the existing concentrating reflectors for the Concentrated PV/T system Absolicon X10. Also, the system has to have enough flexibility to be easy readjusted for the evaluation the focal line of the future concentrated reflectors for the next generation of CPV/T systems.

The methods of learning are described in the Section 1.4; the Absolicon’s administration requirements has allowed defining the operation conditions for which the testing rig has to be created.

First, the measurement head of the system has to be able to work under concentrated irradiation with possible overheating of measurement head’s components. The design of the measurement head has to include the protection and cooling devices to provide the steady work in conditions of the high radiation loads.

Second, the designed equipment has to work in the operation conditions of the open-air measurement site. It means that the mechanical construction; electromechanical components and electronic circuits have to be resistant to humidity and influence of dust in the air.

Third, the designed equipment has to be fully automated and easy in operation to work under minimum control of the personal. Also, the system has to have safeguards to prevent damaging the tested reflector and Sun-walker’s construction in case of improper operation.

Fourth, the obtained information has to be in the form, which is sufficient for the computer processing and storing.

Fifth, the mechanical construction of the system has to have abilities to be easy installed and fastened to the tested reflector. Also the measurement dimension of the system has to cover two conjunct reflectors to evaluate the state of the focal line on the border between them.

As the first step, the array from photo sensors has to be installed on the measurement head to measure the distribution of the solar density radiation.
1.4 Literature review (Existing Methods)

1.4.1 “Skywalker”

The first attempt to create special equipment to estimate the performance of the CPV/T system was made in Australia in 2004. In the framework of the research work, which was conducted at the Australian National University, a device, known as the ‘Skywalker’ module, was designed and built for measuring the illumination flux profile along the focus of a receiver. [2].

Fig. 5 The measurement system for the CPV/T collector’s performance evaluation with the “Skywalker” module.

The Skywalker module consists of a calibrated concentrator solar cell mounted on an aluminum block and encapsulated with silicone and glass. The short circuit current of the solar cell is measured across a resistor, mounted on the back of the block. Water flows through channels milled into the block to keep the cell at a consistent temperature, which is measured by a thermocouple mounted in the aluminum behind the cell. Using results from the solar cell calibration, the radiation flux intensity at the cell can be calculated. The block is mounted on a trolley that is moved along the focal line of the collector by a motor and pulley system (Fig. 5).

1.4.2 Shadow device

For the evaluation the performance of the first CPRs, which were assembled at Absolicon Company, the next simple device with row shading (Fig. 6) was designed [3].

By putting a screen with a row of horizontal slits on top of the trough in a plane perpendicular to the sun and holding a piece of cardboard on the side of the concentrated mirror, a ray pattern will occur on the cardboard and visualize the path of the rays. The ray pattern is photographed and the analysis will show where on the receiver the focal point is. It also shows which part of the parabola reflects light to the focal point and receiver. By studying how much light is reflected onto the receiver, the reflector shape can be evaluated.

However Skywalker’s design is intended to work with parabolic reflectors without the glass cover above the mirror and does not imply any ability to the flexible changing its location in the reflector’s volume. The Shadow device is worth only for the first simple evaluation of the design of the concentrated reflectors.

Fig. 6 The shadow device (Photo by Håkan Håkansson)
1.4.3 Laser Testing rig.

When Absolicon AB Company has extended the production of the reflectors from its own workshop to the plant in Soleftea and put goal to increase the production capacity up to forty reflectors per day, it was decided to arrange the automotive production line. As the first step the mass-line production process was arranged. To test the quality of the produced reflectors it was necessary to create the automotive measurement system. Within the framework of the Master Thesis project the Laser Testing rig was designed and assembled (Fig.7) [4]. The specific task of this measurement system was to get the independent evaluation of the shape of the produced reflectors of the existing design. It means evaluation of the production technology by its ability to produce the reflectors with defined dimension and shape.

Since the relatively small variation in the shape of the parabolic reflectors leads to significant alteration in angel of the reflected radiation and, respectively, to significant variation in location of the focal line and in density of the solar radiation it was important to get the precise tools which would be able to estimate the optic geometry of the produced reflectors. The human ayes cannot provide the necessary accuracy in the test procedure.

To reach the necessary accuracy was possible only using laser radiation of row of semiconductor lasers. The lasers allowed reaching the high precision and repeatability in testing procedure and also independence from the weather conditions that is very important, too.

So, as the Laser-testing rig has to investigate the quality of the existing systems its optic design has to repeat the optic geometry of the reflector-receiver set of the existing system where the laser beam plays a part of the solar beam (Fig. 8).
The construction of the Laser-testing rig includes the Measurement head, the shape of which exactly repeats the shape of the receiver in the solar system.

To evaluate the reflective behavior of the mirror, the five photo sensors from each side of the Measurement head were installed – three of them on the place where the solar cells are located on the receiver (the main area), by one above and below the main area (Fig. 9 - 10).

Respectively, the location of the Measurement head and photo sensors in the reflector’s volume is provided by the Laser-testing rig construction exactly on the same place where the receiver and solar cells are located in existing system (Fig. 11 - 12).

The row from 48 lasers provides estimation of the reflection ability from 48 points (one point per 2 cm.), which composes the measurement line transversely to the central axis of the reflector (Fig.13). The distance between measurement lines is 6 mm. If the reflected beam from any point reaches the photo sensors, the Electronic and Software parts of the Laser-testing rig define the place of the reflected beam and put it in array in the PC memory. If the reflected beam cannot reach any of photo sensors, the zero is put in memory, respectively.
So, in the output, we have the reflection map (Fig. 14), which consists of measurement cells (2 x 0.6 cm), each of them presents the reflection quality on the respective place of the tested mirror. Accordingly the agreement, the measurement cell, which reflects the laser beam on the photo sensor above the main area has to be highlighted by red color, below the main area – by green color, and if the reflected beam reached the main area, the color is yellow. It possible that several photo sensors will be irradiated. If the reflected beam cannot reach any of photo sensors the measurement cell is black.

In general the reflection map can present very proper image of the reflective ability of any mirror’s point. It can reveal the imperfections in production technology and in the quality of the used components and materials.

The Laser-testing Rig is the robust, reliable and relatively fast testing tool intended to evaluate the reflectors of the specific design. But it has strong restriction in the reconfiguration of the measured optic geometry. The construction of the Measurement head and Carriage, which moves along the tested reflector under the laser row, does not imply working with other configurations of the reflectors.
1.4.4 Conclusion.

All testing systems presented above have their own purpose and from the point of view of the conditions worded in Project task have strengths and weaknesses.

The Shadow device (Section 1.4.2) is the simplest equipment to test concentrated mirrors but its operation characteristics does not meet to the demands pointed in Project task. The next characteristics of the Shadow device are insufficient for the future project:
- It does not work automatically;
- The obtained information is not in the form suitable for the computer storage and processing
- It does not work with reflectors of the bigger sizes

The Laser-testing Rig (Section 1.4.3) is intended to estimate the quality of the reflectors of the existing systems as a part of production line. The next characteristics of The Laser-testing Rig are insufficient for the future project:
- It does not work under solar radiation;
- The construction cannot be easily reconfigured for different design of the mirrors and receivers
- The measurement system only defines the presence of the reflected laser beams on the photo sensors but does not estimate distribution of the energy on receiver’s surface

Skywalker (Section 1.4.1) has operation conditions most similar to the conditions of the future project but its construction does not allow working with reflectors with glass cover. Trolleys and cables which support and feed Skywalker make additional shadowing that can affect the measurement accuracy. Skywalker works with one focal line, whereas the solar systems from Absolicon have two focal lines. The mechanical design of Skywalker does not allow flexible changing of the photo sensors location in the volume of the reflector and angel between the photo sensors’ surface and focal line. Also, the mechanical design of Skywalker has restriction to the flexible readjusting to work with reflectors with different shapes and dimensions.
2 SUN-WALKER’S ARCHITECTURE AND DESIGN

2.1 General description

The modern software allows very precise simulating the prospective construction of the designing equipment. However, to predict the future behavior of all components and the whole system being based only on the simulation results is impossible. To obtain the proper information is very important to conduct tests in the real operation conditions. The tests can help to reveal the hidden weakness and to tune the technological process.

For the concentrated solar systems it is critically important to provide the respective design of the reflectors, which would be able to gather solar radiation in the narrow focal line to reach the higher efficiency. Also, it is important to define the best shape of the solar receiver, its dimensions, angel and location relatively the focal line.

The concentration of the solar radiation provides the extremely high thermal load on receiver. Tests allow obtaining information about the behaviour of all components of the future construction in the overheating conditions. (Fig. 15 - 16)

Unlike the design of the reflector, which was used in measurements with Sky Walker [2], the Absolicon’s reflectors have the glass cover above the mirror. This mirror has the small internal rail for the receiver installation into the reflector. So, the final solution is to design the basic frame as a rail for the movable platform with measurement tower. The width of the basic frame less then the internal mirror’s rail does not disturb the reflection from the mirror.

The Measurement platform, which is installed on the measurement tower, has maximum range of discretion to change its location on the tower and tilt angel.

The existing receiver includes the solar cell with 32 mm width. But the company plans to use for the next generation of the solar system new solar cells with 40 mm width. The thermal part usually is for 10-12 mm larger. So, the measurement array has to cover the surface of 54-56 mm.

To estimate the distribution of the density of the solar radiation it was proposed to use 7 photo sensors 8 mm. wide each. The external measurement device NI USB 6008 has eight analogue inputs. The seven inputs are used to measure the signal from the photo sensors and one left for possible input from temperature sensor in future.
The resolution in longitudinal direction is defined by the minimum size of the step of the driving shaft. The existing combination of engine/driving shaft allows reaching the step size of 2 mm. However, high resolution can decrease the measurement speed because it is provided by mechanical components, which have relatively low working speed. To reach the compromise the following solution was found: the software part of the measurement system includes the selective option, which allows tuning resolution from the User Interface.
2.2 Preliminary design and simulation

In the first period under circumstance, which were presented in 1.3 Project task and 2.1 Generic Description, the preliminary complex design was conducted. The constituent parts were defined as well as their operation conditions and interrelationship between all parts.

To help look at the future construction of the Sun-Walker, computer simulation with 3D modeling of the mechanical design was conducted (Fig. 17). The preliminary design of the Software part based on LabVIEW was created.

![Fig. 17 The 3D modeling of the Sun walker](image)

To test the created software the special electronic simulator was assembled. The simulator allows giving a signal similar to the sensors’ signal and to show the DAQ NI6008 output’s state.

The results obtained during the previously conducted designing and testing were considered. The main options of the future construction of the Testing rig correspond to the project’s task, and the real equipment was designed and created.

The complex approach, which includes the simultaneous designing the mechanical, electromechanical, electronic, and software parts, has allowed creating a reliable and easy-to-use device.

So, testing rig consists of the next main parts:

- Mechanical Part, which consists of the basic frame, the self-movable platform moving along the basic part
- Electromechanical Part, which consists of the DC-engine, driving shaft with driving device and sensors which track and restrict the carriage moving
- Electronics Part, which, in turn consists of three subparts – measurement circuit, engine control circuit and power supply with protection circuit
- Software Part, which was created on the LabVIEW basis and provided the general control, collecting and processing the obtained data.
2.3 Mechanical Part
2.3.1 Introduction.

The mechanical construction was created from aluminium profiles and components from the Bosh Rexton Company. Bosh Rexton company produces very well developed nomenclature of aluminium profiles of different sizes and all necessary components, which allow to create very complicated and advanced construction. One of the main advantages is that these components enable to assemble a steady construction, which provides stability for the whole system and at the same time has some potential for easy reconfiguration if it would be needed for the production. The general view of Sun-Walker is presented in Fig. 18. The Sun-Walker is installed in the measured solar system, which consists two reflectors.

The Mechanical part consists of two main components – the basic frame and movable platform (Fig.19)
2.3.2 Basic frame.

The basic frame (Fig.20) is the main load-carrying structure. The construction of the basic frame consists of the one main longitudinal crosstop and two short lateral girders by which the basic frame is fastened on the reflector. On the upper part of the basic frame is installed the driving rail for the movable platform is installed. Also, on the basic frame, the box for the electronic part, components of the electromechanical part such as the driving shaft, motor with gear and mechanical sensors are installed.

2.3.3 Movable platform.

The movable platform (Fig.21) is made from aluminum profile and consists of some components such as the carrier connection box, measurement tower and chain-cable device. The construction of the platform is intended to place the measurement head in any necessary position in the reflector’s volume. The Connecting box and chain-cable device provide the reliable connection photo sensors to the measurement circuit in the box, which is located on the end of the basic frame.
The carrier (Fig. 22) of the movable platform has special following components with ceramics cover to provide precise moving along the rail. To provide proper centering on both butt-ends of the platform the Teflon bears are installed. To transfer the rotation of the drive shaft to the forward movement of the platform the bronze nut is installed into the platform (Fig. 23).

The chain-cable device is fastened to the backside holder on the carrier.
2.4 Electromechanical Part

2.4.1 Introduction.

The electromechanical part is intended for the movable platform moving and defining the measuring point.

The electromechanical part includes the moving system from DC-motor with the gear, driving shaft, and electrical circuits from sensors. The electrical circuit of the electromechanical part is presented in Fig. 24.

2.4.2 Moving System.

The DC-motor is connected to the gear (Fig. 25), which decreases the speed rotation of the driving shaft up to the necessary level and increases the drawing force to provide moving the carriage with installed reflector.

In consequence of the significant length of the driving shaft is sagged on free state. To prevent it, the driving shaft was previously stretched using the special strainer (Fig. 26).

The stretching has allowed making the driving shaft straight and decreasing the load on bearings of the driving device.
2.4.3 Sensors.

On the basic frame, two movement sensors are installed (Fig. 27). The first one defines the start measurement position (Fig. 28); the second one defines the measurement finish (Fig. 29).

The first and the second sensors are located on the outermost sides of the measurement distance and have additional contacts to break the motor feeding line for the immediate stop of the movable platform moving to prevent the Sun-Walker’s construction damaging.

Fig. 27 Movement sensors and their location on the basic frame

Fig. 28 Sensor on the start of the measurement distance
On the driving shaft, the round blind with the hole is fastened. The rotated blind is located between the IR-diode and phototransistor, of the optic sensor (Fig.30). When the hole on the blind crosses the line between the IR-diode and phototransistor the optic sensor generates a signal. It means that the software gets information about every rotation step of the driving shaft. One rotation step moves the movable platform for two millimeters. It is the minimum possible measurement step, which provides the maximum resolution. The user has an opportunity to change the resolution and, respectively, to change the speed depending on the measurement aim.
2.5 Electronic Part

2.5.1 Introduction.

The electronics part is intended to track the triggering of the movement sensors, collect and preliminary amplify the signal from photo sensors, control the motor, and provide communication between the electromechanical part and software part which is installed on the main PC (Fig. 31).

The electronic part consists of NI USB-6008, measurement system and power supply with the protection circuit.

The seven photo sensors are installed into the Measurement head. Other members of the Electronic part and the motor driver are located in the special box (Fig. 32).

Fig. 31 Electronic part

Fig. 32 Box for the Electronic part.
2.5.2 NI USB-6008.

The main component of the Electronic part is the National Instruments USB-6008 data acquisition (DAQ) device (Fig. 33).

National Instruments (NI) offers the complete solutions for the PC-based measurement and control systems. The main idea of the hardware-software complex from the NI is to free engineer-designers from the exhausting work of writing the low level codes, equipment drivers and creating the user interface.

The NI solutions offer all components of the PC-based measurement and control systems – external devices, drivers for these devices and very friendly environment for the creation of the original software.

More than 200 devices from NI and several thousands from other producers can provide all possible kinds of inputs and outputs. From this wide nomenclature it is possible to choose devices with analogue inputs/outputs with different accuracy and sample speed, with very wide range of the input/output voltage and load-carrying ability. From the driver’s options for these devices, it is very easy to choose the type of the measurement – voltage, current, temperature or resistance.

At the designing stage, it was found out that Sun-Walker has to estimate the distribution of the density of the concentrated irradiation on the focal line. Because it was defined that analogue signals will be measured from seven photo sensors and one temperature sensor (for the future improvement) it is necessary to have measurement device with eight analogue inputs.

Also to receive signals from mechanical sensors and optic sensor in Electromechanical part and to control the motor it is necessary to have digital inputs/outputs.
So, to provide control and measurements for the Sun-Walker, NI USB-6008 was chosen (Fig.33). The NI USB-6008 provides connection to eight analogue input (AI) channels, two analogue output (AO) channels, 12 digital input/output (DIO) channels, and a 32-bit counter with a Full-Speed USB interface. Each of the NI USB-6008 DIO/AIO lines can be individually programmed as a static DI/AI or DO/AO line (Fig.34). You can use static DIO lines to monitor or control digital signals and use AIO to measure input analogue signal, respectively, in the conditions which have to be defined in the Software part. [4].

**Specifications**
The following specifications are typical at 25 °C, unless otherwise noted.

**Analogue inputs**
Analogue inputs..........................................8 single-ended, 4 differential, software selectable
Input resolution............................................12 bits differential, 11 bits single-ended
Max sampling rate (aggregate) 1..................10 kS/s
AI FIFO ..................................................512 bytes
Timing resolution .....................................41.67 ns (24 MHz timebase)
Timing accuracy........................................100 ppm of actual sample rate
Input range
Single-ended ....................................... ±10 V
Differential............................................ ±20 V1, ±10 V, ±5 V, ±4 V, ±2.5 V, ±2 V, ±1.25 V, ±1 V
Working voltage...................................... ±10 V
Input impedance...................................... 144 kΩ
Overvoltage protection............................ ±35

**Digital I/O**
Digital I/O
P0.<0..7> .........................................8 lines
P1.<0..3> .........................................4 lines
Direction control.....................................Each channel individually programmable as input or output
Output driver type.............................Open collector (open-drain)
Compatibility ..........................................TTL, LVTTL, CMOS
Absolute maximum voltage range .......–0.5 to 5.8 V with respect to GND
Pull-up resistor ...................................... 4.7 k to 5 V
2.5.3 Measurement system.

The Measurement system is intended to measure the irradiation level in seven points, amplify the obtained signal and transfer it to the DAQ USB 6008. The Measurement system consists of the measurement head and measurement circuit. The Measurement head is installed on the measurement tower and consists of the seven photo sensors, which are located in the special enclosure with cooling radiator and fan (Fig. 35).

![Measurement system](image1)

Measurement head includes the seven photo sensors (which are the pieces of the solar cell) to measure solar irradiation in seven points that allows evaluating the distribution of the density of the solar irradiation with resolution 8 mm. To avoid overheating the photo sensors, they are fastened to the cooling radiator with fan. Also, the construction of the measurement head has the special cover with a narrow slit, which allow passing the restricted amount of the solar radiation and allow increasing the accuracy of the measurements (Fig. 36).

![Measurement head](image2)

The measurement head’s holder design in combination with different construction of the measurement tower (Fig.37) allows putting the measurement head in any desirable place in the reflectors volume not only in the existing solar system but suitably for the experimental testing the construction of the designing future reflectors.
As it was pointed in Paragraph 1.2, Sun-Walker has to provide the verification of the solar simulator. To avoid overheating the components of the Sun-Walker, the design of the measurement head and measurement tower has to locate the measurement head far away from the other components of the Sun-Walker (Fig.38).
The Measurement circuit (Fig. 39) consists of seven identical channels.

Since the solar cells are the current generator, it is very important to measure the current accurately. However, for analogue digital converters it is possible to measure the voltage signals. To measure the voltage signal, which would be equal to the current into the closed loop with solar cell the special resistor was connected. To avoid the disturbances from the resistors for the proper measurement of the photo current, it has to have as less resistance as possible. On the other hand, small resistance leads to a low voltage signal, which could be less then the measurement circuit sensitivity. To choose the proper relation between the accuracy and sensitivity, the following method was applied. The maximum voltage, which could be generated by solar cell is not more then 0.5 V on the infinity load. As the operation amplifier is fed by 5 Volt power supply the output signal cannot exceed this level. So, the amplify ratio was chosen equal 10. To deterrnine the maximum possible current that could be generated under concentrated solar radiation, the following calculations were done. The maximum possible irradiation on the Harnosand altitude is close to 1000 W/m². Respectively, on the focal line the irradiation density can reach the 20000 W/m². The irradiated surface on each photo sensor is equal to 24 mm² (3 mm is the slit’s width multiply for 8 mm. of the photo sensor high). 24 mm² = 2.4 x 10⁻³ m², respectively, the maximum possible output power on this surface could reach 20000 x 2.4 x 10⁻³ x 0.12 = 0.0576 W. As the maximum output voltage from cell is 0.5 V that means that the maximum generated current is 0.0576/0.5=11 mA. So,
to avoid disturbance from possible saturation, the value of the load resistor has to be less than 0.5V/0.011A=45 Ohm. The close value from standard values is 39 Ohm. This resistor was chosen. To check the possible lowest measured signal, the following calculations were done. Input resolution of the AI in USB DAQ 6008 is 11 bit. As the maximum possible output range from the amplifier cannot exceed 5V, the maximum input range in the settings of the DAQ6008 is defined on the same level. Respectively, the voltage resolution of the ADC on the AI of the DAQ 6008 is approximately 0.0025 V per bit. The absolute accuracy at full scale is 15 mV or 0.015 V. So, for the reliable measurements the amount of the input signal on the AI of the DAQ6008 has to be not less than 0.15 V (ten times more than absolute accuracy). It means that on the amplifier input, the signal level has to be not less than 0.15/10=0.015V.

In this case, the measured current on the load resistor can reach 0.015/39=0.000385A=0.385mA. It is possible to calculate the measured reliable minimum of the irradiation density. If irradiation density 20000 W/m² gives 11 mA hence, the measured current 0.385mA corresponds to 20000/(11/0.385)=700 W/m². The concentration rate is 20 and it corresponds to the 35W/m² of the natural solar irradiation density.

To provide the precise calibration and eliminate possible difference of the photodiodes sensitivity, the special variable resistor is included. It can divide the voltage on the load resistor and equalize the sensitivities of all the channels.

In general, it is possible to infer that the measurement circuit has suitable operation conditions, which consists of high sensitivity to weak irradiation on the one hand, and could not be affected by saturation when the irradiation reaches the maximum possible level on the other hand.
2.5.4 Power supply with the protection circuit.

To feed the Sun-Walker’s electronic and electromechanical parts, the special power supply is used. The Measurement system is fed by the +5 Volt line from the NI6008 through the USB connection from a laptop.

![Diagram of power supply and protection circuit]

The additional components, which provide stable +5 Volt for the future extended application, were assembled on the special board together with the protection circuit.

The protection circuit is intended to provide the safety-operating mode from the start. The fact is that NI6008 outputs are established on the high level (+5 V or 1 in binary meaning) when NI6008 is connected to the power (through the USB lines). For some devices in Sun-Walker (especially for the motor), this state is a command for the work start. It was very important to avoid the uncontrollable switching on/off the motor and accidental damaging the in the components of Sun-Walker’s construction.

The protection circuit disconnects the feeding of Sun walker when the power supply starts working. The +12 V from the power supply reaches the transistor base through the limiting resistor and open transistor. The relay on the transistor’s collector starts working and disconnects the feeding of the Sun-Walker’s electronics and electrical parts. The protection circuit’s design is intended to switch on the relay in case if +5 V on the transistor base (the start state of the NI6008 outputs) or if the base is disconnected. All these precautions enable to have only the operating mode controllable by the Software Part of the operating modes. When the software starts working, the state 0 would be established and the Sun-Walker would be fed (Fig.40).
The second precaution is the special Emergency stop button (Fig.41). This button provides immediate disconnection of all power suppliers from the feeding voltage (220 V). It is necessary for the unpredictable events with Sun-Walker's construction and with the operating personnel.

However, the laptop has its own battery, which provides power supply for the NI6008, which receives signals from the second pair of the contacts into the emergency stop button and provides correct finish of the software's functioning.
2.6 Software Part

2.6.1 LabVIEW Overview.

To implement the measurement project the LabVIEW software was chosen. As it was noted in the Electronics Part, National Instruments offers the wide nomenclature of the hardware-software solutions for the measurements and control system. In addition the external DAQ equipment from NI is possible to use with other software environment both from NI and other companies. For example, it is possible to create the system on C+, BASIC and LabWindows/CVI. However, LabVIEW is different from those applications in one important aspect. Other programming systems use text-based languages to create lines of code, while LabVIEW uses a graphical programming language, G, to create programs in block diagram form.

National Instruments LabVIEW is an industry leading software tool for designing measurement, testing and controlling systems. Since its introduction in 1986, engineers and scientists worldwide who have relied on NI LabVIEW graphical development for projects throughout the product design cycle, have gained improved quality, shorter time to market, and greater engineering and manufacturing efficiency. LabVIEW has the flexibility of a programming language combined with built-in tools designed specifically for test, measurement, and control.

LabVIEW is very useful for the specialists with little programming experience especially for the experimental and non-standard measurement and control equipment. LabVIEW uses terminology, icons, and ideas familiar to scientists and engineers and relies on graphical symbols rather than textual language to describe programming actions. LabVIEW has extensive libraries of functions and subroutines for most programming tasks. LabVIEW includes conventional program development tools, so you can set breakpoints, animate program execution to see how data passes through the program, and single-step through the program to make debugging and program development easier.

2.6.2 Virtual instruments

LabVIEW includes libraries of functions and development tools designed specifically for instrument control. LabVIEW also contains libraries of functions and development tools for data acquisition. LabVIEW programs are called virtual instruments (VIs) because their appearance and operation imitate actual instruments. However, they are analogous to functions from conventional language programs. VIs have both an interactive user interface and a source code equivalent, and accept parameters from higher-level VIs. There are the main three VI features:

- VIs contain an interactive user interface, which is called the front panel, because it simulates the panel of a physical instrument. The front panel can contain knobs, push buttons, graphs, and other controls and indicators. The data are input using a keyboard and mouse and the results are viewed on the computer screen.
- VIs receive instructions from a block diagram, which are constructed in G. The block diagram supplies a pictorial solution to a programming problem. The block diagram contains the source code for the VI.
- VIs use a hierarchical and modular structure. They are used as top-level programs, or as sub-programs within other programs or subprograms. A VI within another VI is called a subVI. The icon and connector pane of a VI work like a graphical parameter list so that other VIs can pass data to it as a subVI. With these features, LabVIEW promotes and adheres to the concept of modular programming. An application is divided into a series of tasks, which in its turn could be divided again until a complicated application becomes a series of simple subtasks. VIs are built to accomplish each subtask then combined on another block diagram to accomplish the larger task. Finally, the top-level VI contains a collection of subVIs that represents application of functions. As each subVI could be executed by itself, apart from the rest of the application, debugging is much easier. Furthermore, many low-level subVIs often perform tasks common to several applications, so it is possible to develop a specialized set of subVIs suited to applications engineer-designer can construct.[6]
2.6.3 Data Acquisition

The fundamental task of all measurement systems is the measurement and/or generation of real-world physical signals. Measurement devices help to acquire, analyze, and present the taken measurements.

Through data acquisition, measurement system acquires and converts physical signals, such as voltage, current, pressure, resistance, sound, light, and temperature, into digital formats and transfers them into computer. Popular methods for acquiring data include plug-in DAQ and instrument devices, GPIB instruments, PXI (PCI extensions for Instrumentation) instruments, RS-232 instruments and last years USB-instruments. Through data analysis, raw data are transformed into meaningful information by using curve fitting, statistical analysis, frequency response, or other numerical operations. Through data presentation, data are displayed in a graph, thermometer, table, or other visual display.[7]

The main difference of DAQ measurement systems from other measurement systems is that the software installed on a computer performs the actual measurements. The DAQ device only converts the incoming signal into a digital signal the computer can use. This means that the same DAQ device can perform a multitude of measurements simply by changing the software application that reads the data. In addition to acquiring the data, the application for a DAQ measurement system also uses the software that processes the data and displays the results. Although this flexibility allows having one hardware device for many types of measurements, a researcher has to spend more time developing different applications for different types of measurements. LabVIEW includes many acquisition and analysis functions to help develop different applications.

The computer receives raw data through the DAQ device. The written application presents and manipulates the raw data in a form the user can understand. The software also controls the DAQ system by commanding the DAQ device when and from which channels to acquire data. Typically, DAQ software includes drivers and application software. Drivers are unique to the device or type of device and include the set of commands the device accepts. Application software, such as LabVIEW, sends the drivers commands, such as acquire and return a thermocouple reading. The application software also displays and analyzes the acquired data. NI measurement devices include NI-DAQ driver software, a collection of VIs is used to configure, acquire data from, and send data to the measurement devices.[7]

2.6.4 DAQ-mx

Now there exist two NI-DAQ drivers—Traditional NI-DAQ and NI-DAQmx—each with its own application programming interface (API), hardware configuration, and software configuration.

• Traditional NI-DAQ is an upgrade to NI-DAQ 6.9.x, the earlier version of NI-DAQ. Traditional NI-DAQ has the same VIs and functions and works the same way as NI-DAQ 6.9.x.

• NI-DAQmx is the latest NI-DAQ driver with new VIs, functions, and development tools for controlling measurement devices. The advantages of NI-DAQmx over previous versions of NI-DAQ include the DAQ Assistant for configuring channels and measurement tasks for a device; it increased performance, including faster single-point analogue I/O and multithreading; and a simpler API for creating DAQ applications using fewer functions and VIs than earlier versions of NI-DAQ.

To conduct the measurements and control in the Laser-testing rig the latest version DAQ-mx 8.8 is used. [7]
2.6.5 Simulator

During the test process the Software Part has to obtain data from sensors and send control signals to the actuators through the DAQ NI6008. Development of the Software Part was conducted in parallel with all other parts and it was very important to have on-line information about states on the outputs and simulate signals on the inputs of the NI6008.

To have possibility to estimate the work capacity of the Software Part, special simulator was designed (Fig. 42).

The simulator has 24 digital inputs (composed in three ports), 24 digital outputs (also composed in three ports), two analogue outputs and pin area, which allows to assemble simple electronic circuit.

The simulator was used to test the outputs of the NI6008 and put signal on the inputs according to the logic of action of the Software Part. Also, some components of the Electronic Part were assembled on the pin area to test their communications with the Software Part.

The simulator could significantly improve the designing process of the Software and Electronic Parts.
2.6.6 Algorithm of the Software part

The Software part performs control, measurements, data processing and storing. As the first step of the software execution, it provides secure connection of the Electronic and Electromechanical parts to power supply. Next, according to the Start and Stop sensors’ readings, it defines the movable platform’s location. If it is not on the start or stop positions, the Software part provides movement of the movable platform to the start position. After these preparing steps User interface (Fig. 43) starts.

The Software creates the special folder “Sun Walker test” and subfolders according to the date of the tests for the storing of the tests results. User can input the name of the file, where the result of the current test will be stored. If user does not input the file name, the software automatically names the test file. In the name of the file, the time of the test and start point – “North” or “South” is shown.

The Sun-Walker’s design was performed to be flexible enough to conduct different kinds of tests. In combination with the Electronic part, the software provides reading, amplification, processing, storing and presentation on the user interface data from eight inputs. The current design is intended to measure signals from seven photo sensors on Measurement head and from one reference photo sensor. However, the measurement inputs can be connected to other kinds of sensors, for instance, temperature sensors. Hence, the Software part has several testing modes. The “Movement” mode allows relocation of the movable platform into any point of the measurement distance. In the “Measurement” mode, the movable platform with sensors provides tests in a stable state without movement. Combined “Mov & meas” mode provides measurements on the move. To calibrate sensors before tests, the software has to be switched in the Calibration mode. In the “Measurement” and “Mov & meas” modes, the software provides storing information into files on hard disc.

User interface on special windows presents start and finish points of each test and distance of the measurement point from the start position. The side, which looks Northward in the morning when tested reflectors are targeted on the Sun is named conditionally “North” (it is outside of reflectors) and, respectively, another side is named “South”.

Eight graphical indicators show the levels on the respective inputs.
2.6.7 Data Presentation

During conducting the test, the Software part collects data from DAQ NI 6008 and stores the obtained results in the text file as a table. The stored data includes ten columns (Fig. 44):

1 - distance in millimetres from the start point of the test (North or South)
2 – time stamp of the test point – it is important to have time of the test indicated during long-term measurements in one specific point
3-9 – voltage level from seven inputs (here it is information from seven photo sensors on the measurement head).
10 – voltage level from reference sensor.

The name of the stored file includes the time of the test and start point of the test (North or South). User is able to add his own words in the name of the file.

The format of the stored data is suitable for the opening and processing obtained information in Excel, MATLAB and etc.

The Software part stores the data-files in preliminary created folder Sun Walker and subfolders for every date of tests (Fig. 45)
3 CALIBRATION

Calibration is the procedure intended to match the measured signal to the unit of measurements in which this signal could be represented and stored. A digital measurement system only can measure voltage. It means that any measured signal has to be preliminary transferred into voltage and after that being put on the analogue – digital converter (ADC).

Sun-Walker is the system, which intended to measure solar irradiation in seven points that enables measurement of the distribution of the density of the solar irradiation. The photo sensors (solar cells or photo diodes) transfer the incident radiation into the current. Usually the dependence between incident radiation and generated current is linear. Generated current induces the voltage drop on the load resistor, which is proportional to the current. So, there is the voltage signal which is directly proportional to the amount of incident solar radiation and could be measured by ADC in the DAQ6008. For the calibration procedure, the measurement head, amplifier and DAQ USB6008 were removed from Sun-Walker and are directly connected (Fig. 46).

During the first designing the measurement circuit designing the amount of the load on the resistor and amplification rate of the amplifier were chosen so that the output signal could not exceed 5V when the solar radiation reaches the level of 20 000 W/m$^2$. The additional variable resistor (Fig.47) can decrease the level of the signal in every amplification channel to avoid possible lack in uniformity in the photodiodes sensitivities. However, the artificial light source with guaranteed level of power in 20 000 W/m$^2$ is not available. For the calibration of the measurement circuit was used the artificial source which could provide the irradiation density of 1000 W/m$^2$. As 5 Volts on the output of the amplifier corresponds to the irradiation level of 20 000 W/m$^2$, 5/20=0.25V corresponds to the level of irradiation density of 1000 W/m$^2$. In this case, the calibration procedure comes to setting the value of 0.25 V on all amplifier outputs when photo sensors are located under the irradiation level of 1000 W/m$^2$. 

![Fig. 46 Calibration circuit](image1)

![Fig. 47 Output voltage setting](image2)
To verify the results of calibration under artificial source of radiation, the laser calibration was done. To avoid accidental influence of light sources, this calibration was done in darkness (Fig. 48). As laser can provide a constant level of irradiation, it is possible to compare the measured results obtained from all cells in the Measurement head.

The Measurement head was fixed horizontally. The testing laser was fixed under the Measurement head on the basic frame. Step by step the laser moved and was fixed under all cells to provide the separate irradiation of all cells. (Fig. 49). So, all cells were serially irradiated by the same laser and respectively by the same radiation power. The results from all channels were compared.

However, the laser verification has shown the significant difference in the measured value in the different channels. As the irradiation level and irradiation conditions were the same for all channels, there could be two possible reasons explaining it.

The first possible reason is the variety in spectrum sensitivity of different photo sensors. Laser radiates the monochromatic light with wavelength 0.65-micrometer wavelength. The spectrum of the artificial sun is almost white light, which includes the all-visible spectrum. So the first calibration was done for the integral sensitivity of the sensors. When the monochromatic light irradiates photo sensors, the variety in spectrum sensitivity could give different output results.
The second reason is that combination of the relatively low internal shunt and relatively high series resistors affects the output photocurrent of the sensors especially on the low level of the irradiation density.

To check these suppositions, the new verification procedure was implemented. Using the same artificial light source, new tests were performed on the low level of the irradiation density.

For the additional verification of the calibration was chosen the measurement point with 100 W/m² of the irradiation density was chosen. Respectively, output voltages have to be close to 0.025 V. Since in this measurement white light with spectrum close to the sun’s spectrum was used the possible effect variety in spectrum sensitivity was eliminated. Comparison between the output voltages for photo sensors irradiated by high and low level of irradiation density could reveal the significant variety between the sensitivity of different photo sensors (Fig.50).

All calibration procedures have confirmed the preliminary expressed supposition that solar cell are not so accurate sensors for the measurements. The main advantage of the solar cell is its ability to work under radiation with extremely high intensity and, respectively, in high temperature environment.

It was decided to create the second measurement head with special photo diodes to provide the precise measurements under low-density radiation. (Fig. 51). Photo diodes have extremely high shunt resistance that allows implementing the measurement circuit with reverse bias whereas the low shunt resistance of the solar cells in this case significantly decreases the dynamic measurement...
diapason. The reverse bias circuit for the photodiodes (Fig. 52) has the advantage to be linear in all parts of the measured signal. The size and location of the photodiodes were chosen similar to the photo sensors were made from pieces of the solar cell to provide the same measurement points location.

However, the photo diodes more sensitive to the high temperature, which they can reach working under irradiation with high density. Hereby it was decided to have two measurement heads from photodiodes and pieces of solar cell to calibrate and use under low and high irradiation respectively.

Calibration of the measurement head with photodiodes was conducted under illumination with density in 100 W/m². Verification was done in the same manner using laser calibration tool and under different irradiation from artificial source. Verification has shown the good linearity in all verification points.

A twisted pair to decrease the possible influence from electromagnetic disturbances performed connection of the photo sensors located in measurement heads in both cases.
4 Measurements

4.1 Introduction

The Sun-Walker is a complicated measurement system, which was designed for the specific purpose. It consists of the parts, which were created specially to solve the specific task of estimating the distribution of the density of solar radiation on the focal line of the concentrated parabolic reflectors for the CPV/T solar systems. All parts are unique and do not have any prototype. Being a newly designed system, Sun-Walker and its parts, could have technological and designing mistakes, which have to be revealed and repaired during the trial measurements. To avoid a number of mistakes and decrease the risk of unpredictable behavior of the system, all parts were tested separately before assembling into the whole system. To test the various parts several software applets were created. They allowed testing the Electromechanical part (the motor controllability and the sensors triggering were tested) and the Electronic Part (the distribution of the solar irradiation density from the photo sensors was tested).

The Software part was tested using the special simulator, as it was mentioned in Section 2.5.5. However, the combined work of the all parts could reveal more problems than it was expected before.

4.2 Trial measurements

To provide the suitable conditions for the measurements, the special test system was built (Fig. 53). Two reflectors were assembled in the ordinary manner and Sun walker into these reflectors was installed. The reflectors with tracking device are located on the carrier, which allows movement of the testing device and its horizontal orientation. The tracking system orients the reflectors vertically. When the suitable weather conditions allowed the direct irradiating by the incident solar irradiation, the first trial tests were conducted in the yard close to the Absolicon’s workshop.

Fig. 53 Movable testing system
It was critically important to make up a method, which can provide accurate aiming the tested system at the Sun. For the horizontal aiming the operator has to stay above the center of the line between two reflectors and rotate the carrier to reach the state when the center of his own shadow matches with the line between reflectors (Fig. 54).

For the vertical aiming the traces from focus lines, which usually appeared under sun radiation on the surface of the protection glass, were used (Fig. 55).

If reflector is tilted, so, that these traces are located in the center of the reflector, it provides the proper vertical aiming at the sun’ direction. For the better determination of the reflector’s center the special rule was used, in some specific cases additionally the white paper was used as a screen for more vivid image (Fig. 56). Observance of these two rules provides that perpendicular line to the center of reflectors looks at the Sun.

Sun-Walker can provide measurements, which start from both sides of the main rail. For proper interpretation of the data obtained from Sun-Walker it was decided to name both sides of the rail as North and South. The side, which looks at north when Sun-Walker is aimed oat the Sun, is named North, and another side respectively was named South. The Software part includes note about the start position of any test in the output file.

The numerical data obtained during first tests were processed and the respective images were created for clear presentation of the distribution of the solar irradiation density on the focal lines.

The presented images illustrate the measurement head’s location changing as well as that of clouds and other atmospheric disturbances (Fig. 57-62).
There the location of the measurement head in another place and it shows another distribution of density of solar irradiation. It is possible to observe the gradual transition of the focal center on the first reflector and hopping transition on the second reflector.

Fig. 58 Test 5

First reflector

Second reflector

Fig. 59 Test 6

Fig. 60 Test 7

Fig. 61 Test 8

Fig. 62 Test 9
4.3 Calibration and comparative measurements

During preliminary tests calibration measurements were conducted.

Calibration was done out of doors under the sun. The photo sensors were aimed at the sun using the same procedure as for the whole system (Fig. 63)

During the measurements the amplification for each channel was adjusted to reach the same voltage level on the outputs. It was critically important to identify the minimum level of the input signal to avoid saturation on the highest value. The level of the output signal has not to exceed 5 Volt at the maximum concentrated irradiation on the focal line. The ratio between the reflected area and surface the receiver is 20:1. It means that it is possible to reach the same maximum concentration rate.

However, if focal line is narrower than the width of the receiver, the concentration will be higher. Respectively, the level of the output signal could be significantly higher. As the width of the photo sensors is 8 millimeters, whereas the width of the receiver is 58 millimeters, the possible concentration rate in theory could be seven times higher and reach the ratio 140:1. But the preliminary tests showed that the maximum possible concentration rate has not been higher the 50:1. If the incident radiation has the density around 1000 W/m², the maximum density can reach the value of 50 000 W/m². It means that this level corresponds to the level of the output signal of 5 Volt. Respectively, the amplification of the measurement circuit was set to provide 0.1 Volt under irradiation of 1000 W/m². The density of irradiation was checked in parallel by reference heliometer. These assumptions and calculations about the probable levels of the highest and lowest signal assumed that the measurement circuit and the photo sensors have the appropriate dynamic diapason. To evaluate the real dynamic diapason, the special comparative tests for both measurement heads were done.

The tests were conducted with a reflection protection cover and without it for measurement heads on solar cells and photo diodes, respectively (Fig. 64).
The measurements were done on the same two points for both heads, and cross-section images of the signal levels on photo sensors were obtained (Fig. 65-66).

Output signals for cross-section on the distance 72

Output signals for cross-section on the distance 100

Fig. 65 Profiles of output signals for the same two points of the reflector for the measurements with and without reflective cover on measurement head with photo sensors on solar cell.

The measurements were done on the same two points for both heads, and cross-section images of the signal levels on photo sensors were obtained (Fig. 65-66).

Output signals for cross-section on the distance 72

Output signals for cross-section on the distance 100

Fig. 66 Profiles of output signals for the same two points of the reflector for the measurements with and without reflective cover on measurement head with photo sensors on photodiodes.
These tests could confirm the preliminary assumptions about relatively low quality of the solar cells as the measurement tool for the accurate measuring the light intensity level. Due to the relatively high internal series resistance and low shunt resistance of the solar cell it is impossible to implement the connection of the photo sensors from solar cell with reverse voltage bias. Connection in photovoltaic mode significantly is more sensitive to saturation that results in a low dynamic diapason and significant nonlinearity.

Contrariwise, the photodiodes could show the best results and it became possible to reach the dynamic diapason with ratio more than 50 times between lowest and highest levels. Misgivings, that overheating of the photo diodes under super high intensive irradiation could affect the accuracy of the measurements, were dispelled after the first measurements. The aluminum heat sink, on which photodiodes are installed, dissipates heat effectively enough and the temperature of the diodes has no exceeded 70 degrees centigrade that is significantly less the maximum possible operation temperature (for this type it is 125 degrees centigrade).

The final decision was to continue the next tests using measurement with photodiodes only.

4.4 Interim conclusions, problems to solve and improvements.

The preliminary measurements conducted by Sun-Walker allowed to conclude that in general the behavior of the all the components and the whole system corresponds to the points presented in the Thesis task.

However, the significant faults were revealed too. There are the most important problems which have to be solved to reach sufficient Sun-Walker’s operability. They are:

- Critically high dependence on the atmosphere’s state, which does not allow evaluating the real state of the irradiation on focal line.
- Disability to make measurements in reverse movement direction.
- Bugs in the Software part lead to the unpredictable behavior of the system, including hang-up of the operation computer and loses of the obtained data in case of improper actions of users.
- Susceptibility of the optic sensor on the driving shaft to light disturbances.
- Insufficient flexibility in the movable platform construction not allowing to reach the necessary location of the measurement head.

First, it was important to eliminate or significantly decrease the dependence on the atmosphere disturbances. Testing and comparative measurements imply the stability of testing conditions otherwise it is impossible to separate the faults originated from internal tested system shortcomings and as a sequence from external reasons.

Measurements out of door under the sun always are susceptible to disturbances from different kind events in the atmosphere. Even when the measurements are conducted under pure blue sky, it is impossible to be sure that the high altitude disturbances, which are not recognizable from the earth, do not change the air transparency.

In general the sunlight, which reaches the earth surface, is divided into the two main parts – incident direct beams and ambient diffuse radiation. Various atmosphere phenomena located in different layers destroy the direct sunbeams and transform them in the diffuse ambient radiation. Water vapors include various kinds of clouds, various gases, solid particles and other phenomena, which not only decrease the irradiation level on the earth surface reflecting the sunlight back to space but permanently change the ratio between the diffuse and direct components of the sun radiation which reaches the earth surface. It is critically important for the concentrating system because it is impossible to collect ambient radiation in the focal line. For the proper evaluation of the ability of the concentrating system to collect the solar beams to the focal line it is necessary to create a measurement system, which can relatively effectively eliminate the influence of ambient irradiation and remove disturbances from variation of the incident radiation.
During the preliminary tests it was determined that for the ordinary receiver, the location of the focal line area with reasonably high density of the concentrated incident radiation significantly narrower than the receiver (and, respectively, the measurement head) width. The most concentrated area covers not more than the two photo sensors from seven and by one sensor on both sides of the most concentrated area illuminated by a measurable level of radiation. It was assumed that photo sensors with the least level of irradiation were affected the ambient radiation only. It has allowed finding relatively easy way to remove the influence of diffuse radiation on the test’s results. The software was updated by special subroutine, which can determine the lowest level of irradiation from all sensors for each measurement point and subtract it value from all values of other sensors. This procedure allows obtaining the zero level of the incident irradiation for any measurement point and for any time independently on the ratio between ambient and incident components in solar radiation.

The next solution could extract the incident component of the solar radiation. It was decided to implement a reference photo sensor, which measures the direct incident solar radiation (Fig. 67).

![Reference sensor's connection circuit.](image)

The reference sensor includes two photo diodes where one of them is opened to the solar radiation and the second one is located in the shadow under the special shadow cover, which protects the photodiode from the direct incident component. The photodiodes are connected in reverse voltage bias with load resistors (Fig. 68). Voltage drops on the diodes’ load resistors
corresponds to the level of the whole and ambient irradiation, respectively. Discrepancy between these voltages corresponds to the level of the incident component of the solar radiation. This signal is put on the last amplification channel, which was left for possible additional application. The amplified signal comes in analog input of the DAQ NI 6008 and in the Software part, respectively.

To calibrate the reference sensor the shadow cover has to be temporary removed, and rotating the variable resistor the state, when the output signal is equal to zero, has to be reached. It means that under the same radiation both photodiodes generate the same voltage on respective load resistors. When the shadow cover comes back and protects one of the diodes from direct radiation, discrepancy between the voltage drops exactly corresponds to the incident component of the solar radiation at any time of the tests. Scaling the obtained signal from the photo sensors on the measurement head to the signal from reference sensor at the same time eliminates disturbances from non-stable transparency of the atmosphere. The tests have shown the high effectiveness of the founded solution. It allowed obtaining the reliable data, even when high altitude clouds clouded the sky (Fig 69).

![Fig. 69 Fleecy/cirrus high altitude clouds.](image)

However, the test conditions, when the sun was totally hidden by low altitude high density clouds, the tests could not be conducted because the level of the solar irradiation density decreased up to the level significantly less then the amplification circuit’s sensitivity – approximately 100-200 W/m². It was impossible to recognize the sun location at all.

According to the results obtained during the preliminary tests, the Software part was updated significantly. Additional steps were implemented, which allowed conducting the test procedures in both directions. It has increased the speed of the test’s procedure and removed the part of time, which before was spent to wait the movable platform coming back to the start position. The conception of two start positions- North and South start positions was developed and, respectively, the code in the Software part responsible for the storage of the data in file was updated to put the start position’s name in the name of the file. In addition to storing the distance point together with the data from photo sensors was implemented the function to store the date stump. It is a very useful function to determine the test’s time during the long-term measurements in one specific point of the reflector in the test mode without movement.

To make the Software part more resistant to the improper user’s actions, additional sets of codes were implemented to prevent unpredictable behavior of the Software part and the whole system in general. Also, the Software part has the ability to discover the possible loss of connection with the electronic part and states of emergency stop. In all situations when the Software part finds possible errors in the Sun-Walker components, it provides secure finishing the test execution and disconnection from power supply.
During the preliminary tests under solar radiation, susceptibility of the optic sensor on the driving shaft to light disturbances was revealed. The photo transistor in optic pair, which tracks the rotation of the driving shaft influenced by sun light comes into saturated state and gives a false signal in the Software part. To avoid the false triggering of the optic sensor the special protection cover was made and installed round the optic sensor (Fig. 70)

The design of the measurement head was improved to provide more flexibility in the measurement head’s location. The support arm, on which the measurement head is fastened, was truncated to provide larger angle of head’s tilt. However, it decreased ability to move the measurement head in transversal direction. To retain and increase its ability in the design of measurement tower the additional mechanical component was added, which could improve the whole flexibility of the tracking system (Fig. 71)
5 Results and conclusions

5.1 Introduction

During the trial measurements, the proper adjustment of all components of the Sun-Walker was conducted. In most cases, the behavior of the system was close to the options, which were outlined in the project task. However, the significant number of mistakes and unpredictable events were revealed. It is a very common situation in designing new equipment. The tests have helped to change some components in the Mechanical part to make the Sun-Walker user-friendlier in operation. The hardware and software upgrades have made the system much more resistant to different disturbances. Also, the improvement of the User Interface made it intuitive obvious.

After implementing the last improvements in the Software part the last version was composed in the Install set. This set includes the main program, a special utility for the preliminary processing data obtained from Sun walker and drivers, which support the external equipment (namely NI6008). After that the set was installed in the Sun-Walker's computer.

5.2 Tests’ results

In the last version of the Sun Walker design, different kinds of tests were conducted in different conditions. The test results are stored in the file in the row state to allow different processing of the obtained data. To remove the disturbances caused by shady atmosphere phenomena the data from the photo sensors on the measurement head were scaled up to the reference level of the solar irradiation obtained from the reference sensor.

The special algorithm to eliminate the effect of instability of the irradiation level due to instability of the atmosphere’s transparency was implemented into the special additional utility, which is the part of the Sun-Walker’s software set. It reads the stored row data from the table file, finds the lowest value between the output values of all the photo sensors per every measurement point and expresses the obtained value as amount of the diffuse ambient irradiation in this measurement point. After that, the utility subtracts this value from output values of all the photo sensors. At this step the influence from the ambient irradiation is removed. At the next step, the utility finds the maximum value for all measurement points and normalizes all output values for all measurement points and for all sensors to the obtained maximum value. In parallel, the same normalization is executed for the data from reference sensor. At the final step, the utility scales up the preliminary normalized data from the photo sensors on the measurement head to the preliminary normalized values of the reference sensor. Scaling up is executed for every measurement point. The normalized data from the photo sensors on the measurement head are scaled up to the normalized value of the reference sensor on the same measurement point.

The implemented method has restriction in usage in the condition where irradiation falls less than approximately 200 W/m\(^2\). As it was shown above, the maximum possible level of the density of the solar irradiation was preliminary assumed (and later confirmed) as 50 000 W/m\(^2\). As the input signal on the operational amplifier cannot exceed the 5Volt level in the operational conditions for this type of amplifier, it was decided to set an equal to this voltage level to the maximum density irradiation of 50 000 W/m\(^2\). Respectively, during the calibration, the value 0.1 Volt was determined to be equal to the irradiation 1000W/m\(^2\) permitting to reach the maximum possible dynamic diapason. The signals with level below the 0.02Volt related to noise and have random behavior, which cannot present properly the existing irradiation if their density is less then 200 W/m\(^2\). However, for the reference sensor, the output level of 3 Volt was equated to the irradiation level of 1000 W/m\(^2\) and it can give reasonable data for the irradiation level 10-20 W/m\(^2\) (approximately equal to 0.02Volt as the output signal). So, on the one hand there is a reasonable value obtained from the reference sensors and absolutely random distribution for the stored value from the photo sensors measurement head. Respectively, determination (and respectively, its subtraction from the values from all the sensors) of the lowest value as a value, which is equal to the ambient component of solar irradiation becomes wrong because of random character of all these data. However, this restriction is not so important for most test application because it is relatively easy to choose for...
tests the time periods with irradiation significantly higher than 200 W/m² when the processing method can effectively remove influences of atmospheric disturbances.

For the more vivid presentation of the high effectiveness of the performed method, some results from the tests were used, where solar irradiation has shown significant instability.

To show clearly how the implemented method can improve the obtained data and clean it from light disturbances, in addition to the images, the curves of distribution of solar density irradiation in longitudinal direction are presented for some of the photo sensors (usually for the central photo sensors with high intensity of irradiation).

![Graph showing data comparison](image)

Data directly from sensors

Processed data

There is possible to observe the impact level from the processing algorithm on final data depending on the variation of the reference level of irradiation

Presentation of the results of the Test N6 in 3D and plane view before scaling to the reference level of irradiation

Presentation of the results of the Test N6 in 3D and plane view after scaling to the reference level of irradiation

Fig. 72 Results of the test N6
To evaluate the repeatability of the results of the measurements in both directions, the special test was conducted (Fig. 74). The test was conducted on the first steps of the measurements on the Sun-Walker’s final version, and it was possible to note some saturation points. Later, when
the possible highest and lowest levels of irradiation on photo sensors were determined and, respectively, was defined the dynamic diapason, the amplification was decreased, and became possible to avoid the saturation on the measurement outputs. These two tests were conducted immediately back-to-back to avoid the influence of the sun movement. The start points of the first measurement correspond to the finish points of the second one and they most significantly differ by the measurement time. It is possible to note some discrepancy in the data distribution because of the sun shift.

The figures show curves for all the photo sensors for the row and processed data. Owing to stability of solar irradiation (see. Reference level’s line) the curves from row and processed data are superimposed and only on the start point it is possible to note some discrepancy. These superimposes confirm the ability to remove disturbances properly.

Sun-Walker has the mode to make measurements in any specific point along the basic frame. It is important when it is necessary to track the changing in the distribution of the irradiation on the focal accordingly the sun movement. Some tests were conducted when the measurement head stood stable on one specific point in the reflector (Fig. 75). The whole time of the test was approximately one hour. The figure demonstrates the common trends in the changing of the photo sensors’ value according to the sun movement and variation, which correspond to the instability of the solar radiation. The curves of the reference sensor’s value and pairs consisted of the curves of value for row data and processed data for each of all photo sensors are presented. The discrepancy between the curves in pairs is especially notable in those measurement points where significant variations in solar radiation took place.

![Fig. 75 Long-term test on the one measurement point without measurement head’s movement](image_url)
5.3 Conclusions

The tests, which were conducted in different atmospheric conditions, allow making the following conclusions.

The designed Sun-Walker has shown the operational capabilities, which correspond or exceed the options, which were defined in the Project task.

The Sun-Walker’s design could eliminate one of the most significant shortcomings of one of its prototype test system, Sky-Walker, ([2] and Fig. 5 paragraph 1.4.1) – disability to conduct measurements under glass protection cover. The mechanical design of Sun Walker provides ability to conduct measurements on the low height under reflector surface. However the high design flexibility of Sun-Walker at the same time permits after simple reconfiguration to conduct measurements on larger distance to the reflector systems with one focal line, these system to measuring system was created Sky Walker. So, the mechanical design of Sun Walker has wider ability to readjust to different kinds of reflectors with different sizes.

Using the highly robust and light aluminum components in combination with high precision rail, on which the measurement platform move, gives high mechanical steadiness and, respectively, high precision in measurements.

The Electromechanical components can deliver measurement platform in any points of the measured reflectors with high speed and accuracy.

My suggestion was to use LabVIEW as a software platform, which could be used by a designer without great experience in high-level programming. At the same time LabVIEW has all necessary tools to provide control, measurements and transforming the obtained information into a suitable form. It has allowed reaching the sufficient results in relatively short time.

So, the created Laser Testing rig shows the operational conditions, which corresponds to the conditions, which were defined in the Project task or exceeded them.

The system is fully automated, flexible to readjustment, protected for the measurements outdoors and easy in use.
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